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# The contribution of science to risk-based decision-making: lessons from the development of full-scale treatment measures for acidic mine waters at Wheal Jane, UK

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## Abstract

The use of risk-based decision-making in environmental management is often assumed to rely primarily on the availability of robust scientific data and insights, while in practice socio-economic criteria are often of considerable importance. However, the relative contributions to decision-making made by scientific and socio-economic inputs are rarely assessed, and even less commonly reported. Such an assessment has been made for a major remediation project in southwest England, in which some 300 l/s of highly acidic, metalliferous mine waters are now being treated using oxidation and chemical neutralisation. In the process of reaching the decision to commission the treatment plant, a wide range of scientific studies were undertaken, including: biological impact assessments, hydrogeological investigations of the effect of pumping on the flooded mine system, and hydrological and geochemical characterisation, together with integrated catchment modelling, of pollutant sources and pathways. These investigations revealed that, despite the spectacular nature of the original mine water outburst in 1992, the ecology of the Fal estuary remains remarkably robust. No scientific evidence emerged of any grounds for concern over the estuarine ecology, even if mine water were left to flow untreated. However, a rare ecological resource known as "maerl" (a form of calcified seaweed) is harvested annually in the estuary, providing significant revenue to the local economy and underpinning the 'clean' image of local sea water. Social and environmental benefit surveys revealed strong public perceptions that any visible discoloration in the estuary *must* indicate a diminution in quality of the maerl, to the detriment of both the public image and economy of the area. This factor proved sufficient to justify the continued pump-and-treat operations at the mine site. Although the decisive factor in the end was socio-economic in nature, robust assessment of this factor could not have been made without robust scientific evidence. It is concluded that investment in investigating and contributing to the formation of public perceptions is just as important as investing in scientific investigations per se.


*Keywords:* Acidity; Decision-making; Mining; Risk; Science; Socio-economic; Water; Wheal Jane

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## 1. The role of science in environmental decision-making

It is widely accepted that decisions relating to environmental protection and restoration should be based on sound scientific understanding of the natural world. Given that scientific understanding of many environmental compartments and stressors is limited, either due to lack of investment in measurements or to the virtual impossibility of making pertinent observations without altering the system and thus invalidating the measurements (an instance of Heisenberg's Uncertainty Principle), it is generally also agreed that it is most appropriate that technical assessments of options for environmental management be undertaken in "risk-analysis" mode. Such an approach has long been established practice in the radioactive waste disposal sector (e.g. Corbett, 1988; Cohen, 2003) and, more recently, it has gained pre-eminence in the field of contaminated land remediation (e.g. Petts et al., 1997; DEFRA, 2002). As this type of approach is enjoying ever-wider uptake in the sphere of environmental engineering, it is timely to scrutinise whether science-based risk analysis is really living up to its name. The key question in this regard is: to what degree are scientific investigations and findings *truly* the key drivers in environmental decision-making?

In this paper, a contribution is made to answering this question by means of a major case-study. This case study involved the development of a risk-based case for implementing large-scale remediation measures following a high-profile environmental 'disaster'. The importance of scientific investigations was evaluated within the overall decision-making process, which also took account of a wide range of diverse socio-economic factors. The case study in question specifically concerns one of the most severe instances of mine water pollution yet documented in Europe (the case of Wheal Jane, Cornwall, UK). The key lessons drawn from this example are potentially applicable to a broad range of environmental remediation challenges well beyond the specific topic of mine waters.

## 2. Context of case study: water pollution from abandoned mines

Mine water pollution is an increasingly prominent cause of water quality degradation in the current and former mining areas of the globe. While many jurisdictions successfully implement regulatory regimes which ensure compliance with high emission standards from active mining sites, particular problems arise in the post-abandonment phase, especially where no clear 'problem-owner' can be identified. With no responsible party to implement treatment measures, polluted water can flow unabated from abandoned mine workings. As if this were not bad enough, it is commonly found that water quality deteriorates markedly, with contaminant concentrations often increasing by as much as a factor of 10, during the process of flooding of mine voids which follows the withdrawal of dewatering pumps (e.g. Younger, 1997). This deterioration in water quality is due to the sudden dissolution of all soluble, pollutant-storing secondary minerals, which have hitherto been 'high and dry' above the water table. Although water quality will gradually improve over subsequent years as flushing processes remove the worst of the polluted water from the mine (e.g. Younger, 2000), long-term water quality will often be still too poor to favour discharge to natural watercourses without prior treatment. Hence, the need for someone to take care of aquatic discharges from a particular mine can often be felt in perpetuity—a problem for even the most durable of private companies. Sooner or later, the majority of mines are likely to end up without a non-governmental 'problem-owner'. This situation can arise in a number of ways, amongst which the following are prominent:

- specific legal exemptions for operator responsibility for post-abandonment pollution (which was the case in the UK, for instance, until the end of the 20th Century)
- liquidation of the mining company upon closure of the mine (an increasing problem as marginal mines in nearly exhausted mineral fields are often left in the hands of small, locally based mining companies which lack the financial resources to survive mine closure)
- failure of governmental agencies to recognise an impending mine water pollution threat, given that it can take years (and in some cases even decades) after mine closure before surface outflows commence

– where closure of a mine leads to polluted discharges emerging not from the mine entrances belonging to the last mine operator in the area, but from some other old shafts or adits located downstream, which are not in the ownership of the last company to mine in the catchment.

All of the above problems have been encountered several times in Europe and North America over the last few decades, and the general weakness of polity and regulatory awareness in this field means that further examples will likely occur in future in many mining districts around the world.

## 3. The Wheal Jane mine waters: initial outburst and aftermath

The following overview is deliberately brief, given the ready availability of more detailed accounts of the mine water outburst of 1992 and its aftermath (e.g. NRA, 1994; Banks et al., 1997; Bowen et al., 1998; Younger, 2002). Albeit the account which follows effectively corrects some minor errors in previous accounts, the level of detail provided below is aimed primarily at facilitating the reading of this paper in isolation, and readers with a specific interest in the Wheal Jane case study from a mine water management perspective are advised to consult the various papers cited above.

The abandoned Wheal Jane Tin Mine is located in southwest Cornwall, England (Fig. 1). Mining on the site was first recorded in 1778, although it is thought to have started in pre-Roman times. Mining recommenced in the early 1960s with the development of a new mine on the site. This new mine also experienced a brief period of closure from May 1978 to September 1979, during which time the underground services were almost wholly destroyed by corrosion wrought by the acidic waters in the mine. The final recent period of working at Wheal Jane lasted from the autumn of 1979 (Davis and Battersby, 1985) until March 1991, during which period the ownership of the mine changed hands three times. By dint of being connected underground to an extensive network of very old, long-abandoned mines, Wheal Jane had to carry an exceptionally heavy dewatering burden, and it had an installed pumping capacity reaching 200 l $s^{-1}$ by 1990. Sporadic government subsidies helped to ease the economic burdens of this very high dewatering rate, but the expiry of a period of subsidy in the late 1980s left the mine economically vulnerable. When the market price for tin plummeted in early 1991 to just over £2000/tonne, the mine immediately became unviable. Underground operations ceased on 6th March 1991 and the mine was formally abandoned on 9th September 1991. Following the cessation of pumping in March 1991, the mine water level in the workings gradually rose, and by November 1991 the water level was near surface and so limited pumping was commenced on 16th November 1991 from one of the mine shafts, with discharge of the pumped water into the Clemows Valley Tailings Dam (Fig. 1), which was still operative at this time, as it received tailings derived from the processing of ores brought to the site from the South Crofty mine, which was still in production. On 17th November 1991, water started to issue from the Janes Adit (Fig. 1) and on the 20th November 1991 the adit was plugged. Treatment was suspended on 4th January 1992, due to the high turbidity of water discharged from the CVTD, and the mine water was allowed to accumulate in the abandoned workings. On 13th January 1992, an uncontrolled release of a very large volume (variously estimated at between 25,000 and 50,000 $m^3$ in a 24-h period) of metal laden, acidic mine water occurred from the Nangiles Adit into the Carnon River. Although this outburst has been widely attributed to failure of a plug in the portal of the Nangiles Adit (e.g. NRA, 1994; Bowen et al., 1998), more recent investigations have shown that no such plug existed and the abruptness of the outburst was actually due to the sudden failure of a pile of roof-fall debris which had been impounding the acidic water above the invert level of the Nangiles Adit (Younger, 2002). The released water contained in excess of 3500 mg/l of dissolved metals (principally iron, zinc, cadmium, arsenic, aluminium, plus other traces of toxic metals; Table 1). As a result, the zinc and cadmium Environmental Quality Standards (EQS) for the Carnon River (500 μg/l $Zn^T$ and 1 μg/l $Cd^T$ (NB the superscript 'T' denotes total concentrations)) at Devoran Bridge were exceeded by 900 and 600 times, respectively. The magnitude of this sudden outburst utterly overwhelmed the dilution capacity of all downstream watercourses, and resulted in the development of a

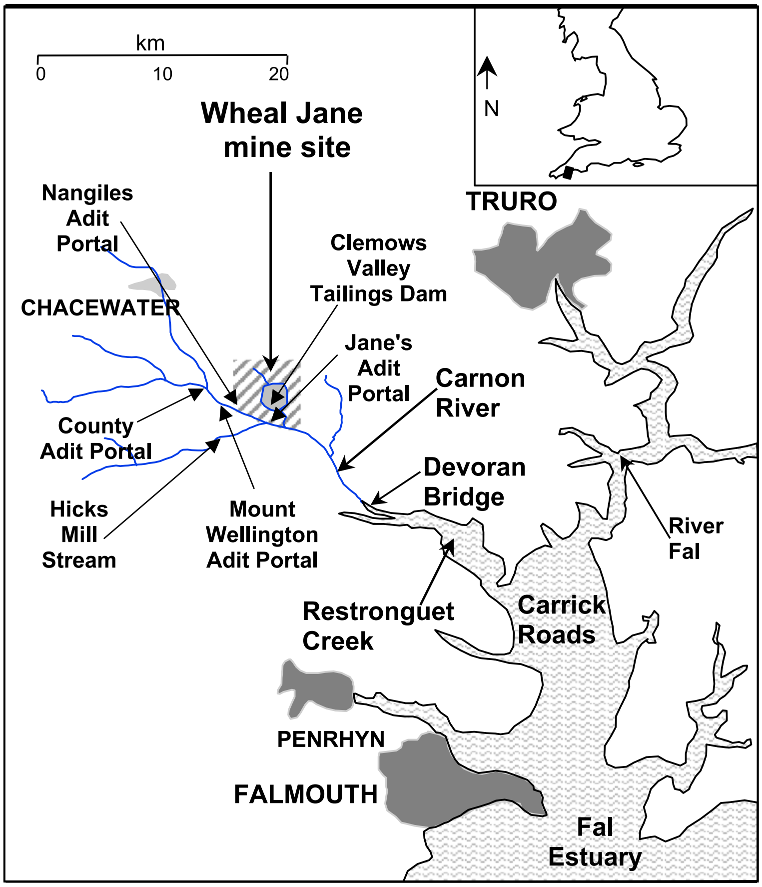


Fig. 1. Sketch map of the Wheal Jane area Cornwall, UK, showing major settlements, and the locations of surface water features and adit portals mentioned in the text.

highly conspicuous orange plume of contaminated water in the estuarine and marine waters of the Fal estuary. The progress of this highly visible plume was captured by airborne cameras of the national and international news media, who did not hesitate to describe the incident as an "environmental disaster".

Table 1
Peak metal concentrations measured in the Carnon River on 14/1/92 (after KPP, 1999)

| Determinant | Peak concentration (total metals, μg/l) | EC dangerous substances directive—fresh water EQS (for hardness >250 mg/l) |
|---|---|---|
| pH | 3 | 6–9 |
| Arsenic | 6000 | 50 (dissolved) |
| Cadmium | 600 | 1 |
| Copper | 7000 | 28 (dissolved) |
| Iron | 600 000 | 1 000 (dissolved) |
| Nickel | 1 200 | 200 (dissolved) |
| Zinc | 440 000 | 500 |

Although the flow from the Nangiles Adit soon decreased, a substantial residual flow of highly contaminated water continued to emanate from the Nangiles Adit. In response, emergency treatment was immediately recommenced, and sufficient pumping capacity was installed in the Wheal Jane No. 2 Shaft to maintain the mine water level below the invert of the Nangiles Adit. Lime was added to the pumped water to neutralise the acidity and remove the dissolved metals as a gelatinous precipitate. The treated mine water was discharged into the Clemows Valley Tailings Dam (CVTD), which was used to both settle and store the precipitated solid. Supernatant water was discharged from the dam to the Carnon River via a polishing lagoon. During 1992/1993, the National Rivers

Authority with the assistance of the mine owners, progressively upgraded the capacity of this emergency treatment system from 58 to 330 l/s by replacing the original No. 2 Shaft pumps with six Grundfos 55 l/s pumps and by the installation a new lime dosing plant. This temporary treatment works continued in operation until the commissioning of a purpose-built treatment works in October 2000. This paper documents the investigations undertaken between 1992 and 1998 to identify the best long-term option for the control of the mine water at Wheal Jane. These investigations were undertaken in two phases. An initial "Environmental Appraisal and Treatment Strategy" study (Phase I) was undertaken between 1992 and 1994. This was followed by the Phase II "Appraisal and Selection of Long Term Treatment Option" study carried out between 1996 and 1998. Following completion of Phase II, a contract was let for the design, construction and operation of the long-term treatment plant. Tendering took place in 1998/1999, with the long-term treatment plant being commissioned in October 2000.

During the period of investigation, the flow rate of water requiring interception and treatment varied between about 90 and 300 l $s^{-1}$. However, the quality of the water improved over time (Fig. 2). In line with experiences elsewhere (Younger, 1997), an exponential decrease in metal concentrations was observed, as the previously accumulated oxidation products were gradually flushed out of the mine. Eventually, the concentrations declined to residual values consistent with the long-term release of metals from ongoing pyrite oxidation in and above the zone of water table fluctuation. Although the studies undertaken between 1992 and 1998 predicted long-term average iron and zinc concentrations of 296 and 77 mg/l, respectively, these have continued to decline and average around 150 and 50 mg/l at the time of writing (November 2003). Neal et al. (this volume) provided an indication of the wide range of containments in the River Carnon as fed by the Wheal Jane Mine discharge.

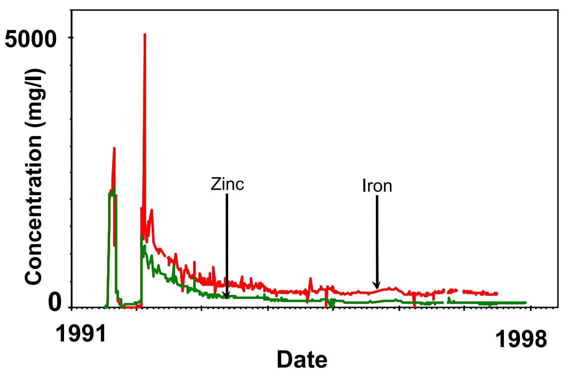


Fig. 2. Decline in concentrations of iron and zinc in raw mine water discharged (by natural outflow or pumping) from the Wheal Jane mine, 1991–2003.

## 4. Drivers for remediation planning at Wheal Jane

In the immediate aftermath of the spectacular outburst of 13th January 1992, the objective pursued by the National Rivers Authority was to minimise any further impacts on the environment by restoring the Carnon River to pre-incident conditions. Essentially, steps were taken to ensure that there was no degradation in water quality whilst studies were undertaken to develop long-term treatment water quality objectives and identify a suitable treatment strategy. The Phase I studies which were completed in 1998 revealed that the treatment measures implemented in the wake of the outburst had not only restored the Carnon River to pre-incident conditions, but had in fact achieved an overall improvement in water quality. Bearing this in mind, the following water quality objectives were adopted for further scrutiny during the Phase II investigations:

– 'No Deterioration', i.e. to maintain the improvement in Carnon River quality achieved by the treatment regime adopted after the January 1992 outburst.
– 'North Sea Objectives', i.e. compliance with undertakings made by the UK government at the North Sea Ministerial Conferences, which had set specific objectives for decreasing the emissions of ecotoxic substances to the coastal waters of northwestern Europe. In the case of the Carnon River, these objectives implied that it would be necessary to achieve a reduction in the mass of zinc discharged into the sea via the Restronguet Creek from 309 tonnes/year to less than 62 tonnes/year.
– 'EQS', i.e. compliance with the Environmental Quality Standards (EQS) set out in the European

Union Dangerous Substances Directives, which in the case of the Carnon River were established as specific exceedance thresholds for cadmium, zinc and copper at the Devoran Bridge Statutory Monitoring Station (which forms part of the National Water Quality Monitoring Network).

During the Phase II Wheal Jane Study, the above objectives were refined to become the comprehensive list of options summarised in Table 2. The breadth of the options listed in Table 2 essentially represents a risk hierarchy, with the 'do nothing' option corresponding to an uncritical acceptance of all environmental risks potentially associated with the mine water discharge. The Lower-Order Objectives represent a tightening of risk tolerance to eliminate some of the more extreme impacts potentially associated with the discharge. Progressively narrower risk tolerance is implied by each of the Higher-Order Objectives. As the investigations unfolded, it gradually emerged that it would not be possible to achieve the Higher-Order Objectives without either provoking negative environmental impacts elsewhere (either in the catchment or in other areas, where raw materials needed for achievement of the highest order objectives would need to be sourced). In the end, the decision-making process boiled down to the pursuit of the level of mine water treatment that would yield minimal environmental risk (=maximisation of environmental improvement) without incurring excessive costs (i.e. the so-called 'Batneec' approach). Part of the rationale of this approach is that high costs for a given treatment option are often in themselves a surrogate measure of environmental *damage* elsewhere: this is arguably so, for instance, where limestone quarrying in one area of major landscape value (e.g. the Derbyshire Dales) is pursued in order to produce lime for acidic drainage treatment in another (western Cornwall). The objective listed in Table 2 therefore simplified to a three-way choice:

– no treatment, i.e. to permit polluted water to flow freely to the Carnon River
– pump and treat at the Wheal Jane No. 2 Shaft, using the maximum feasible pumping capacity (i.e. six submersible pumps in the shaft in parallel), recognising that during times of peak flow there may still occasionally be an element of uncontrolled drainage from the Nangiles Adit
– treat *all* sources of polluted mine water in the Carnon Valley, which would mean not only pumping and treating at Wheal Jane as above, but also having similar treatment plants to handle any overflow form Nangiles Adit as well as the perennial discharges from the County Adit and Mount Wellington Adit; in addition, some means of intercepting a wide range of diffuse pollution sources in the Carnon Valley, both in the headwaters (mainly spoil heaps and a redundant tailings dam) and lower floodplain areas (thick deposits of tailings from a former period of mining when riverine disposal of tailings was practised).

Selection between these three options raised a host of technical questions, the resolution of which is summarised in the following sections.

Table 2
Water quality objectives defined during the phase II investigations

| Objective | Broad categorisation | Water quality objective |
|---|---|---|
| 1 | Do nothing | No treatment (baseline) |
| 2 | Lower-order objectives | No deterioration |
| 3 | | No discolouration |
| 4 | | North Sea declaration commitments |
| 5 | Higher-order objectives (EQS Compliance) | Protection of estuarine biology |
| 6 | | EC dangerous substance directive—fresh water EQS |
| 7 | | EC dangerous substance directive—salt water EQS |

## 5. Scientific methodologies used

Given that this investigation covered such a vast range of scientific disciplines, it is not possible to provide a detailed account of all methodologies used in this study in the space available here. Full accounts are available in the library of project reports maintained by the Environment Agency (EA) in Exeter (UK). Suffice it to note the following:

– all sample collection (hydrochemical, sedimentological and biological) and flow monitoring was undertaken in line with the EA's established, nationally approved procedures, which include rigorous QA/QC measures and associated statistical analyses.

- all laboratory chemical analysis was undertaken by laboratories accredited by the UK Analytical Accreditation Scheme (UKAAS), and as such was undertaken using well-known, formally adopted standard operating procedures and QC measures.
- laboratory identification of biota was undertaken by specialist technicians at the Plymouth Marine Laboratory, using nationally adopted identification keys.
- mathematical modelling of flows and geochemical reactions was mainly undertaken using well-established software with long histories of use and publication, including the MIKE11 and MIKE22 hydrological simulation codes (both proprietary software of the Danish Hydraulic Institute) and the public-domain MINTEQA2 hydrogeochemical simulation code, produced by the US EPA.

Further details on some of the specifics of application are given within the discussion of insights obtained below.

## 6. Scientific insights

### *6.1. Biological impacts of the 1992 outburst and subsequent mine water outflows*

Because of its long history of acidic mine drainage, the Carnon River has long been used as a research and teaching resource for aquatic biologists. There thus exists a substantial body of archival data pre-dating the 1991 mine closure from which the pre-existing ecological status of the various reaches of the drainage system can be defined. Substantial, intensive monitoring in the wake of the 13th January 1992 mine water outburst facilitates the identification of possible impacts of the new mine water discharge by means of comparative studies. The findings of these comparative studies are summarised below, following the drainage system downstream from the freshwater Carnon River through the tidal reaches of Restronguet Creek, thence into estuarine waters of the Carrick Roads and the lower Fal Estuary (for locations, see Fig. 1).

#### *6.1.1. Carnon River*

The physical characteristics of the Carnon River are such that it would be expected to sustain a substantial salmonid fishery were it not for the poor quality of its waters. While non-migratory brown trout are present in those tributaries of the Carnon River and Restronguet Creek which drain un-mined catchments, the Carnon River itself has been observed to be utterly devoid of fish throughout its length, both long before and after the events of 1991–1992. In addition, the Carnon River has long been (and remains) almost wholly devoid of aquatic macrophytes and benthic macroinvertebrates downstream of the village of Chacewater (Fig. 1), which approximates the point at which diffuse inputs of mine water begin to dominate in-stream chemistry. This lack of plants and invertebrates contrasts markedly with similarly sized tributaries of the Fal estuary which are not subject to mine water pollution. The picture which emerges is that the January 1992 outburst, and all subsequent inputs of mine water from Wheal Jane, entered a receiving watercourse which was already virtually devoid of macrobiota.

#### *6.1.2. Restronguet Creek*

The tidal, brackish waters of the Restronguet Creek (Fig. 1) are ecologically poised in such a way that they not only show signs of chronic impacts from mining-derived metals pollution but are also susceptible to further degradation. Before the January 1992 outburst, the macrobenthic, nematodal and phytoplanktonic communities of the Restronguet Creek were already distinctively metals—impacted in comparison to other similar tributaries of the Fal estuary. No noticeable deterioration in these already-impoverished communities was observed after the 1992 spill. A similar picture emerges with regard to the shellfish beds (cockles, mussels and periwinkles) in the Creek, which have long exhibited measurable bioaccumulation of copper, zinc and/or cadmium. However, there are some indications that the wildfowl of Restronguet Creek were affected by the spill and subsequent outflows of polluted mine water.

Between 1992 and 1995, the swan population of the Creek showed increased mortality, which has been tentatively attributed to the elevated releases of untreated mine water from the Nangiles Adit in that period, as installed pumping capacity struggled to keep up with a string of record-breaking peak flows from the mined voids. The tentative conclusion is that, in contrast to the highly degraded habitat of the Carnon River, the Restronguet Creek still has something to lose from any further deterioration in water quality.

#### *6.1.3. Carrick Roads and Fal Estuary*

In the Carrick Roads and the rest of the Fal estuary, neither the chronic nor temporary inputs of mining-associated metals have been found to be associated with unequivocal deleterious biotic impacts. Although the Carrick Roads host one of the UK's few commercial oyster fisheries, no demonstrable impacts of ecotoxic metals have been evident either before or after January 1992. Anecdotal evidence suggested an increased incidence of green-tinged oysters in autumn 1992, which it was inferred might be associated with elevated concentrations of copper in the estuarine waters. However, not only can such green tingeing arise from causes other than copper pollution, but oysters with this colouration actually command a higher price than regular oysters, due to the fact that popular traditions in France ascribe aphrodisiacal properties to green oysters! Hence, whatever slight biological impacts this anecdote might signal, in terms of the value of the oyster fishery the impact was, if anything, positive.

Hence, despite the undoubtedly ecotoxic nature of both the January 1992 outburst waters and the subsequent untreated discharges via the Nangiles Adit, biological impacts have been few and equivocal. In part, this is because the potentially grave impacts on the Carnon River were limited by the fact that it did not possess a healthy biota prior to the Wheal Jane outburst, being already subject to severe metals pollution from other sources of mine water pollution in the catchment (most notably the County Adit, Fig. 1). Since it is impossible to kill something which is absent, the outflows from Wheal Jane did not produce a demonstrable biological impact in the Carnon River. In relation to the estuarine waters downstream, which inter alia host southern England's most significant colony of maerl (a form of calcified seaweed which is of very high conservation value; Birkett et al., 1998), it has emerged that, apart from equivocal findings in relation to swan mortality in Restronguet Creek, inputs of mine waters via the Carnon River cannot be correlated with any notable ecological impact. This perhaps surprising finding can likely be explained by a combination of diluting inputs from other uncontaminated tributaries and by density stratification of the estuary, which seems to have promoted transport of mine water contaminants out to sea, thus largely preventing significant metals contamination of the benthos within the estuary. Thus, the estuarine circulation system seems to have repeatedly assimilated the potentially toxic inputs from Wheal Jane by means of dilution and dispersion.

### *6.2. Hydrological and geochemical investigations: I. Ground water catchment of Wheal Jane*

Early in the Phase I investigations, it became apparent that a quantitative understanding of the relationship between pumping rates and drawdowns in the Wheal Jane system would be needed in order to derive operating rules to minimise episodes and magnitudes of uncontrolled mine water discharges from the Nangiles Adit. Preliminary attempts to model yield-drawdown responses in the system using conventional groundwater modelling software (the ASM finite difference code) were unsuccessful. It was found that adjustment of model parameters to match observed drawdowns at the pumping shaft always resulted in substantial over-prediction of drawdowns in the more distal parts of the system, such that the model would be predicting no chance of uncontrolled discharges from the Nangiles Adit when these were known to be occurring. On reflection, it was realised that this behaviour was due to the assumption of laminar flow which is inherent in all standard finite difference groundwater models which are predicated on the validity of Darcy's Law. With most of the flow in the Wheal Jane system actually occurring through large-diameter roadways and open stopes, the flow regime is far more likely to be turbulent rather than laminar. In other words, Darcy's Law is inapplicable to flooded mine systems like that of Wheal Jane. These findings echoed the contemporaneous experiences of researchers working on other flooded deep mine systems (e.g.

Sherwood and Younger, 1994). As in these other studies, the conventional groundwater modelling software was abandoned in favour of a custom-written semi-distributed, non-Darcian hydraulic model, in which flow was assumed to be rapid and head losses were modelled using turbulent flow formulations. This representation of the system succeeded in reproducing observed incidences of overflow from Nangiles Adit as a function of pumping rate and water levels in the No. 2 shaft, adjusted according to the time of year (more pumping being needed to achieve the same drawdown in winter than in summer). Using the results of this unorthodox but effective simulation approach, operating rules for the No. 2 Shaft pumping operations were devised and successfully applied throughout the Phase II study period.

As might be anticipated, both data inspection and modelling confirm that most of the groundwater catchment feeding the No. 2 Shaft corresponds to the zone underlain by mined lodes. Two important complications arising from this ought to be mentioned. Firstly, because of the disposition of the mined lodes (which strike approximately ENE–WSW) the groundwater catchment feeding the pumps at the No. 2 Shaft underlies more than one surface water catchment. Hence, where the Hicks Mill Stream crosses the lode outcrop, it tends to lose water to the subsurface, augmenting the total flow which eventually reports to the No. 2 Shaft pumps. Similarly, notwithstanding the existence of a long concrete lined section where it crosses the lode outcrop, there is evidence of a certain amount of leakage to the workings through the bed of the Carnon River in the vicinity of Nangiles Adit. It used to be considered that the County Adit was an entirely separate hydrological system from Wheal Jane. However, following the flooding of Wheal Jane a noticeable deterioration in quality of the County Adit waters occurred in January 1992, with Cu rising from 1 to 3 mg/l, Cd from 4 to 12 μg/l, and Zn from 3 to 6 mg/l. Improvements in water quality subsequently occurred, closely mimicking the trends seen in the Wheal Jane discharge itself (Fig. 2). The existence of a direct connection between the Jane workings and the County Adit was therefore evident. It was subsequently discovered that, during periods when the County Adit carries very high flows, it also loses a substantial amount of water to the Wheal Jane workings. In 1999, during a period of low flows which allowed safe access into the County Adit, the locus of this leakage was identified and sealed off. Leakage of waters to the workings also occurs during wet periods at innumerable, largely unidentified locations scattered across the hillsides above the Carnon Valley, where 'gunnises' (open stopes) intersect the ground surface and capture overland flow. Given all of these sources of indirect recharge to the Wheal Jane groundwater catchment, the actual surface 'footprint' of this catchment is very much larger than one would deduce simply by studying the drawdown patterns associated with the pumps in the No. 2 Shaft.

In terms of groundwater chemistry, two types of simulation were developed. Firstly, a well-known analytical solution to the one-dimensional advective dispersion equation (Sauty, 1980) was adapted to represent the flushing of recently flooded mine voids by fresh recharge. Although this model was successfully used by Younger (2000) to reproduce the observed exponential decline in iron concentrations in the No. 2 raw pumped water (Fig. 2), it was incapable of extension to take account of the dynamics of other solutes such as zinc, cadmium, arsenic and sulphate. Rather, simulation of the behaviour of these solutes was approached by means of geochemical modelling using the public-domain code MINTEQA2.

Detailed simulation of the geochemistry of the major mine water inputs to the Carnon River (essentially the Wheal Jane system, with or without treatment, and the County Adit) was necessary to provide boundary conditions for surface water transport modelling, and to generate scenarios of future water quality both for evaluation of alternative objectives (Table 2) and as support for treatment design. In pursuit of these ends, simulations using MINTEQA2 were designed to address the following three questions:

(i) In what forms (species) do the key contaminants occur in the mine waters?
(ii) Which contaminants are most likely to be removed from solution as precipitates?
(iii) Which contaminants are prone to sorption?

Inspection of data from both County Adit and Wheal Jane reveals that the annual maximum concentrations of contaminant metals tend to coincide with peak flows, which generally occur in winter. Accordingly, the MINTEQA2 simulations were based on samples of mine water from times of peak concentrations. In relation to question (i) above, it was found (as anticipated, given the low pH) that Cd, Cu, Zn, Mn and Fe are all largely present in solution as unassociated divalent cations ($Cd^{2+}$,$Cu^{2+}$, etc.). Iron was also predicted to be significantly complexed with hydroxide, forming the monovalent cationic species $Fe(OH)_2^+$. However, the metalloid arsenic behaves differently from the true metals, being present exclusively in anionic form, as the complex $H_2AsO_4^-$. In terms of question (ii) above, only iron showed a strong tendency to form precipitates, which is consistent with observations of significant quantities of ochre in the County Adit and the various adits at Wheal Jane. A few data points suggested that Cu might be likely to precipitate as cupricferrite, and Mn as manganite; however, neither of these two metals has been found to form a significant component of suspended solids in the mine waters. No precipitates of Cd, Zn or As were predicted to form.

In relation to question (iii) above, i.e. the propensity of contaminants to sorb to solid surfaces, none of the metals were predicted to sorb significantly. This is not surprising, since at low pHs the surfaces of most minerals are positively charged, due to the accumulation of a coating of protons ($H^+$). Metal cations cannot effectively compete for these sorption sites, and thus tend to remain in solution. However, because of its anionic occurrence in solution, arsenic can sorb significantly at low pH, and solid:liquid distribution coefficients in the range 2–12 were predicted for arsenic in the pH range 3–5 relevant to Wheal Jane and the County Adit. Analytical support for this prediction was subsequently forthcoming, as analyses of sequential extractions from suspended sediments versus dissolved components yielded approximately equivalent distribution coefficients in the range 0.5–10, with an average of 2.6, for samples which yielded pH values in the range 3.8–4.1. This compares well with a median model predicted distribution coefficient for arsenic in this same pH range of 2.7.

When the above findings were incorporated with hydrological data in a predictive spreadsheet-based model, good agreement was obtained between observed concentrations of the metals and arsenic and predicted values. This provided a solid basis for generating boundary conditions for subsequent simulations of contaminant transport through the Carnon River and the estuarine waters downstream.

### *6.3. Hydrological and geochemical investigations: II. Carnon River and tidal waters*

In the wake of the January 1992 outburst, the intensities of flow measurement, water quality sampling and hydrodynamic characterisation activities in the Carnon River and the Fal estuary were all increased substantially. Two new, permanent gauging stations were installed on the Carnon River: one just upstream of the confluence with the treated mine waters coming from Wheal Jane, and the second at the tidal limit and EQS reference point at Devoran Bridge. These replaced earlier, less expensive gauging structures which had long given rise to difficulties in the development of reliable stage-discharge relations. A further previously established gauging station at Twelveheads (near Chacewater; Fig. 1) was retained in service. Small gauging stations of less permanent construction were also constructed at the County Adit, Nangiles Adit and the effluent point from the Wheal Jane treatment system below the Clemows Valley Tailings Dam.

Once several years' worth of data had been obtained from the new gauging stations on the Carnon River, rainfall-runoff modelling of the Carnon catchment was undertaken using the NAM component of the MIKE11 code, taking advantage of a high-quality 35-year rainfall record from a Meteorological Office rain gauge (Trevince) located within the catchment. These simulations served the following purposes:

- they allowed correction and re-use of some of the data obtained from the superseded gauging stations on the main channel of the Carnon River
- they allowed extension of observed flow records for all gauging stations (including all Carnon River stations *and* the individual mine water discharges) back to 1952, greatly extending the range of flow conditions against which the various objectives (Table 2) could be assessed.

In the estuary, an updated, high-resolution bathymetric survey was completed and a number of drogue surveys were undertaken to characterise patterns of water movement (and thus potential pollutant dispersion) during different phases of the tidal cycle. Two low-flow dye tracer tests, and a single high-flow test, were undertaken in 1997, with release of tracers in the Carnon River and sampling in the Restronguet Creek and Carrick Roads. These tests provided direct evidence of dispersive behaviour, against which model simulations could be calibrated. Coupled with long-term tidal records and flow data from the Carnon River, this information provided the platform for comprehensive simulations of advective–dispersive transport of pollutants through the Fal estuary system.

The data collected using the above infrastructure (as well as synthetic data extended back to 1952 using rainfall-runoff modelling techniques) provided the basis for the development of an integrated catchment model. Given the enormity (amounting to practical infeasibility) of attempting to simulate all groundwater, river and estuary flow and solute transport processes using a single simulation platform, the development of this integrated catchment model actually involved the coupled application of distinct software packages and simulations for various compartments of the entire system. Where one model provided boundary conditions for another, extensive consistency checking was undertaken to ensure that no inconsistencies were introduced during the transfer of data from one platform/format to another. The entire suite of models which were integrated in this manner comprised:

- seven rainfall-runoff models
- six hydrochemical models for the various pollutant source zones in the Carnon Valley, each of which included representations of the following key parameters: Fe, Cu, Cd, Zn, Mn, As and pH
- a MIKE11 flow model of the Carnon River and Restronguet Creek, to which a water quality component was externally coupled (i.e. one of the six hydrochemical models referred to above, which in turn was coupled to the other five models)
- a MIKE21 flow and transport model of the Restronguet Creek, Carrick Roads and Fal estuary.

Once all initial inconsistencies had been removed, and the correlations between simulated results and observed data maximised, this complex suite of models was used to predict daily variations in the metal load discharged into the Carnon River, and thence into the estuarine waters, from the principal sources of contamination (Wheal Jane Mine, County Adit and various diffuse sources). Fig. 3 summarises the findings of the modelling exercise in relation to the contaminant loadings derived from these various sources. The numbers quoted relate to the entire catchment to the tidal limit at Devoran Bridge. The percentage figures relate to total concentrations of the elements indicated at Devoran Bridge. The compliance/failure plots show the factor by which Water Quality Objectives (=EQS) at Devoran Bridge are exceeded at Devoran Bridge, for the specific scenarios and pollutants in question. The 35-year flow records used for calculating time-series in these plots are based on simulation of rainfall-runoff responses for the catchment for the period of observed record, and are taken to represent the range of conditions likely to be encountered over any 35-year period in the future. These modelling results clearly demonstrate the dominance of Wheal Jane and the prominent contribution of the County Adit. However, they also reveal that metals for which very low tolerances are established in EQS criteria (especially Cd and, to a lesser extent, Cu) are also sourced from a range of diffuse sources.

Having established this robust ability to represent pollutant sources in the catchment, it was possible to use the model in predictive mode to analyse water quality implications of various treatment scenarios relevant to the assessment of the objectives listed in Table 2. The results of these simulations showed that without treatment, water discharged from Wheal Jane would be the major source of pollution in the Carnon River (cf. Fig. 3), and consequently none of the water quality objectives listed in Table 2 would be achieved. By contrast, model results clearly indicated that continued treatment of the Wheal Jane mine water up to a maximum flow of 300 l/s would achieve all of the Lower Order objectives set out in Table 2. Only limited further improvements in water quality would be achieved by making provision to treat the rare peaks of flow from Wheal Jane above the 300 l/s threshold, and these improvements would not be sufficient to attain the Higher Order objectives. Further model runs incorporating treatment of the

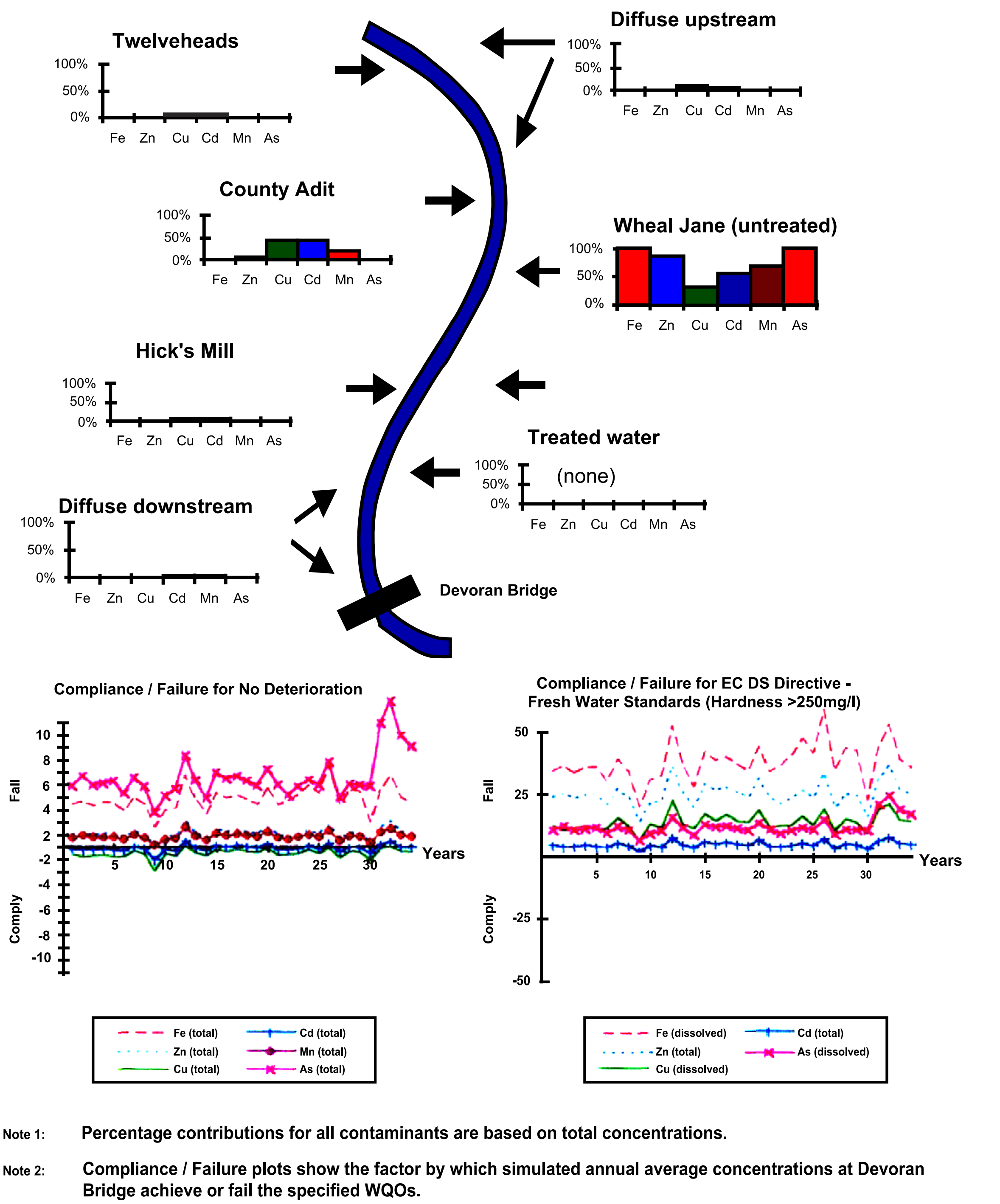


Fig. 3. Discrimination of relative contributions of various contaminant sources in the Carnon Valley, as derived from the application of the integrated catchment modelling approach described in the text (adapted after KPP, 1999).

County Adit waters in addition to those from Wheal Jane showed that, despite some improvement in water quality, even this measure would not be sufficient to achieve the Higher-Order water quality objectives for either the river or the estuary. In fact, the modelling confirmed that the only measure which would achieve compliance with the Higher-Order Objectives (Table 2) would be to treat the entire flow of the Carnon River immediately upstream of the EQS compliance point at Devoran Bridge. However, this would entail leaving the entire catchment polluted down to that point. This would achieve only cynical, bureaucratic EQS compliance which is hardly in keeping with the spirit of the legislation which EQS are set to serve. Most interestingly, the model simulations strongly suggested that, even were all of the flow of the Carnon River treated at Devoran and returned to the channel, diffuse pollution sources downstream of Devoran Bridge would quickly lower the quality of the river water below EQS standards once more. It was therefore concluded that there was no feasible way of achieving the Higher-Order objectives, and consequently achievement of all Lower-Order Objectives by means of continued pumping and treating of the Wheal Jane mine waters alone, to a total capacity of 300 l/s, was the only realistic intervention.

### 6.4. Discoloration events: analysis of triggers

The dramatic outburst of 13th January 1992, which caused such widespread discoloration in the Fal estuary, had heightened local sensitivities to any further visible staining of waters in the Carrick Roads. The question therefore arose as to what degree of treatment would be required to ensure that future discoloration events would be avoided. An employee of the Environment Agency whose home adjoined the Restronguet Creek had kept a diary of occasions on which discoloration had been observed in the Creek and the Carrick Roads after the initial outburst of January 1992. Logically, one would expect these discoloration events to bear some relation to measured iron concentrations in the Carnon River at Devoran Bridge. Preliminary statistical analyses confirmed the existence of just such a relationship. Once the integrated catchment model was available, it was used to quantify the relationship between observed discoloration and iron loading passing Devoran Bridge. It was concluded that discoloration in the Restronguet Creek will not occur as long as iron loading is below 2000 kg/day, but that discoloration can be expected to be visible in the Creek once iron loadings exceed a threshold lying somewhere between 3000 and 4000 kg/day. Discoloration of Carrick Roads does not occur until a much higher iron loading threshold (lying somewhere in the range 6000–8000 kg/day) is exceeded at Devoran Bridge. By further applying the integrated catchment model to predict discoloration frequencies for various treatment scenarios, it was concluded that without active treatment at Wheal Jane, the Restronguet Creek would be perceptibly discoloured two to three times per year on average, whereas with treatment of Wheal Jane up to a maximum capacity of 300 l/s, discoloration events would be very rare, with an average frequency of only one to two events per decade.

### 6.5. Mine water treatability investigations

Whilst the above investigations were underway, an engineering-oriented investigation was undertaken to identify the most appropriate treatment technology for application at the Wheal Jane site. The full range of available treatment technologies, spanning both active and passive unit processes (Younger et al., 2002), were investigated iteratively, during Phases I and II of the overall evaluation process.

At the time of the January 1992 outburst, passive treatment of acidic mine waters had only just begun to be discussed in the international literature, based on pilot plant studies undertaken in the late 1980s–early 1990s in Colorado (Cohen and Staub, 1992). Although it seemed unlikely that this technology would prove sufficiently powerful to cope with the very high flow rates and metals concentrations being encountered at Wheal Jane, a certain amount of optimism in relation to the eventual outcome of early improvements in water quality (Fig. 2) lent weight to the proposal that pilot plant studies of passive treatment be undertaken at Wheal Jane. A very large pilot passive treatment plant (PPTP) was therefore constructed in the floor of the Carnon Valley, and a small amount of water (around 2% of the total flow emanating from the mine) was passed through this system, facilitating extensive experimental investigations of passive treatment. The scientific findings of these investigations are discussed in detail in the other papers in this volume, and will therefore not be mentioned at all here. However, it must be noted that, interesting as these findings were, at no time did the performance of the PPTP provide any grounds for imagining that passive treatment could play a significant role in the treatment of the Wheal Jane discharge. With the benefit of hindsight, it is now clear that the PPTP suffered from an unfortunate design flaw in that it was essentially configured "back-to-front": acid-generating aerobic processes were sited upstream from the crucial alkalinity-generating anaerobic processes. This configuration contrasts sharply with more recent passive treatment designs (e.g. Younger et al., 2002) and with the latest European Union guidelines on passive mine water treatment (PIRAMID Consortium, 2003).

In parallel with the PPTP research, the search for an appropriate technological solution for the Wheal Jane mine waters continued. The preliminary short-list of potentially applicable long-term treatment technologies was made on the basis of process suitability, robustness and whole life cost (including capital and operating costs). Three treatment technologies were identified as potentially suitable, i.e. oxidation and chemical neutralisation (OCN), biochemical sulphidisation (BCS) and ion exchange (IEX). The BCS and IEX options both offered the possibility of recovery of saleable forms of copper, cadmium and zinc from the waters. However, even though the Wheal Jane waters contain very high concentrations of these metals in comparison to most mine waters, it soon emerged that none of them could be recovered economically (i.e. the costs of the extra energy input needed to yield the metals in recoverable form exceeded the market values of the metals thus obtained by very wide margins). Substantial pilot plant testing was undertaken at site for the OCN and BCS options. The BCS tests indicated an ability to reliably achieve low residual concentrations of all target metals (Table 3), though the residual arsenic concentration was not quite as low as that achieved by OCN. The latter technique also proved capable of achieving very low residual concentrations of key metals (Table 3), albeit it could not quite match the performance of BCS in relation to copper. It did, however, show the best performance of all three techniques in relation to arsenic.

Table 3
Performance and costing comparisons for the principal active treatment technologies assessed for potential use in long-term treatment of Wheal Jane mine waters

| Contaminant | OCN | BCS | IEX |
|---|---|---|---|
| | Achievable residual concentrations[a] (after full treatment using indicated method) for key contaminants in the mine water | | |
| Arsenic | 10 | 50 | 50 |
| Aluminium | <250 | <250 | 10 |
| Cadmium | 1 | 1 | 1 |
| Copper | 40 | 20 | 5 |
| Iron | 1300 | 500 | 1000 |
| Manganese | 140 | 50 | 10 |
| Nickel | 100 | 200 | 50 |
| Zinc | 400 | 50 | 40 |
| Sulphate (mg/l) | 1000 | 100 | 1000 |
| Capital costs[b] | £4.25M | £6.26M | £12M |
| Annual operating costs[b] | £0.76M | £1.85M | £1.4M |

[a] μg/l except for sulphate.
[b] At year 2000 prices, relating only to the final option involving 300 l/s of water pumped from the No. 2 Shaft and treated on land near the shaft.

Table 3 summarises the residual metals concentrations achievable by all three active treatment technologies, along with estimated capital and operating costs. IEX is much more expensive than both other options in capital costs, and even though it is less expensive than BCS in operating costs, it still has a much higher net-present value than BCS when discounted over a 25-year design life. The substantial difference in annual operating costs between BCS and OCN was found to relate primarily to two factors: (i) the costs of reagents and (ii) the costs of sludge disposal (due to the sulphide sludges produced by BCS requiring more costly handling and disposal than the hydroxide sludges produced by OCN).

Although the combination of performance and costings given in Table 3 clearly favoured OCN, it was decided *not* to pre-judge the final technology selection, but to leave this to the market by means of open competitive tendering. Contractors were invited to submit tenders for the design, construction and operation of the treatment facility for an initial period of 10 years, based on a preferred treatment technology of their own choosing. The tenders were adjudicated using a model that considered the track record of the process, process robustness and cost. Thus, the Wheal Jane process selection was made on a combination of economic and technical considerations rather than the process being selected purely on a scientific basis. The process finally selected for long-term treatment of the Wheal Jane discharge was OCN, using the variant of the technology known as the ‘High Density Sludge’ (HDS) process. The Wheal Jane HDS plant was commissioned in the autumn of the year 2000, and in its first winter of operation it successfully removed more than 1000 tonnes of metals from the mine water. It has since continued to work very efficiently, exceeding the expected performance indicated in Table 3. Full details of the design and operation of the Wheal Jane plant are given by Coulton et al. (2003).

## 7. Socio-economic constraints

Early in Phase II of the Wheal Jane investigations, it became obvious that the various alternative objectives outlined in Table 2 were likely to carry very different price tags. Anticipating that cost would become an important issue in reaching the final decision, a socio-economic benefit analysis was undertaken to establish the level of treatment that could be justified in terms of the resultant environmental benefit. This analysis was developed in parallel with the technical investigations described above. The concept of ‘willingness to pay’ was used to assess the monetary value associated with each of the options listed in Table 2, with all objectives being normalised against the option of doing nothing. Estimates of the benefits to the recreation, tourism and other relevant industries were determined for each water quality objective, together with an assessment of the potential benefits to properties surrounding the estuary. This indicated a significant economic benefit in preventing extensive discolouration of the estuary, with little additional benefit achieved by preventing occasional short-term discolouration or achieving full environmental water quality compliance. The largest single beneficiary of treatment was identified as the calcified seaweed industry in the Fal estuary, which annually harvests up to 35,000 tonnes of dead maerl from the beds located below the low tide mark in the estuary, which is then processed and sold for use as a soil conditioner. It was found that frequent, extensive discolouration of the estuary would lead to the perception that the maerl could be contaminated with heavy metals, potentially resulting in the loss of revenue in the local economy amounting to around £1M per annum. Minimisation of discoloration thus acquired central importance in the overall decision-making process.

Comparison of the monetary benefit for each of the Table 2 objectives with the whole life cost of treatment (capital and operational costs; cf. Table 3) revealed that continued treatment of the Wheal Jane mine water was the only option with a net positive value (i.e. with benefit value greater than the treatment cost), as this alone could achieve the necessary minimisation of discoloration, and treatment of further pollutant sources would neither achieve EQS nor further improve the avoidance of discoloration. Thus, the socio-economic evaluation also favoured the adoption of a long-term treatment strategy involving pumping and treatment of up to 300 l/s of Wheal Jane mine water.

## 8. Utility of scientific findings in identifying a long-term remedial strategy

A whole host of scientific investigations were carried out in the pursuit of a long-term remediation strategy for this pollution source. Given the scale of investment in scientific work, it is worthwhile examining the contribution which the findings of these investigations made to the overall decision-making process.

The framework for all investigations is the array of the legal commitments of the UK government, most notably the European Union’s Dangerous Substances Directive (currently in the process of being subsumed into the Water Framework Directive, which was enacted in the year 2000) and the ‘North Sea Accords’, which are the outcome of multi-lateral negotiations at ministerial level between individual EU Member States and other territories (including Norway and a number of small British dependencies) which lie outside the EU concerning the need to reduce pollutant inputs to northwestern European continental shelf waters. These two driving pieces of legislation are, of course, based to some degree on science, though they also embody many pragmatic political and economic decisions.

In consideration of the above framework, the overall ‘drivers’ for the Wheal Jane project evolved over time, leading to the identification of a range of potential objectives, ranging from the high-risk ‘do nothing’ option to the highest-order objective of achieving full EQS compliance throughout the Carnon River and Fal estuary. While integrated catchment modelling certainly helped to clarify what is actually achievable in this catchment, it was socio-economic benefit analyses which eventually identified avoidance of discoloration as the principal, economically defensible driver for maintaining a capacity to treat up to 300 l/s of Wheal Jane mine water in perpetuity.

The most valuable scientific contributions to the decision-making process were those associated with integrated catchment modelling, which in turn were utterly dependent on the hydrometric and water quality sampling activities. The biological characterisation of the Carnon-Restronguet-Fal estuary system was principally of use in helping to eliminate the ecological sensitivity of the Carrick Roads as a potential driver for decision-making: in the final remediation planning stages of Phase II, it was not necessary to further interrogate the biological data sets and models. The hydrogeological investigations of the Wheal Jane groundwater catchment were principally used in defining the pumping regime necessary to avoid uncontrolled outflows of polluted water from the Nangiles Adit, and thus in the definition of a design pumping rate of 300 l/s for the long-term treatment system. However, evidence gathered during these investigations also facilitated careful consideration of possible “preventative measures”, to help minimise the amount of water which needed to be intercepted for treatment. Most options considered (e.g. sealing places where old mine voids emerge at surface, impermeabilising streambeds to prevent leakage to workings), had either already been implemented during mining, were prohibitively expensive or were incompatible with conservation requirements and/or other socio-environmental goals. In the end, only one real preventative option was identified: preventing occasional underground overspill of water from the County Adit system to the western parts of the Wheal Jane lode system, which was accomplished in 1998 by means of repairing underground diversion walls. The very detailed investigations of passive treatment undertaken as part of the Phase I and II investigations actually contributed nothing to the decision-making process besides underlining the early deduction that only active forms of treatment would be sufficient to treat the highly voluminous, heavily contaminated waters at this site. However, these studies (and the more recent investigations reported in the other papers in this volume) *have* advanced scientific understanding of the ability of natural biogeochemical processes to improve the quality of acidic mine waters, therefore potentially contributing to the further application of passive technologies and similar biotechnologies at appropriate sites elsewhere in the world.

In terms of wider sustainability issues, one of the principal concerns which has been identified relates to the fact that OCN treatment involves the continued input of lime, which in this case is produced from limestone quarried in Derbyshire. The production process involves roasting the limestone in kilns to break down the limestone into useable lime (calcium oxide) and release of the potent greenhouse gas carbon dioxide. Additional resources are used to grind the calcium oxide into powder and transport the resultant lime to Cornwall. Treatment of the Wheal Jane mine water therefore results in the release of greenhouse gases and the consumption of fossil fuels. The other key sustainability issue is the production of large quantities of iron hydroxide sludge. At present, these are being disposed of on-site, within the Clemows Valley Tailings Dam. When space in this location is exhausted, land-filling on another part of the mine site is likely to be needed in the medium term. Although research is actively underway to find beneficial uses for these iron-rich sludges (e.g. as reagents for stripping phosphate from sewage or agricultural runoff, forming a Fe- and P-rich material which is then attractive as a slow-release fertiliser; Heal et al., 2003), at the present time land-filling remains the most economic option. Viewed in the light of these observations, the overall sustainability of the treatment process now in place at Wheal Jane remains questionable. However, given that the more environmentally benign “passive” treatment technology is simply not applicable at this site, the treatment option actually selected for full-scale implementation has been designed to use the minimum quantity of chemicals consistent with achieving acceptable water quality, and therefore overall provides the least environmental impact and hence the most sustainable option in this instance.

## 9. Conclusions

In this case, as we suspect in many others, scientific investigations proved to be *necessary* to the decision-making process, though they did not in themselves prove *sufficient* for this purpose. In essence, the role of scientific investigations in the development of the risk-based case for remediation at Wheal Jane was not as the ultimate arbiter, but rather as an essential support to resolution of an issue which ultimately hinged on socio-economic considerations. The key driver for remediation design in the end was the avoidance of visible discoloration of the Restronguet Creek and Carrick Roads, in order to avoid giving rise to speculation about the integrity of harvested maerl produced from the estuary. It should be noted that scientific evidence had clearly shown that there would be no grounds to doubt the integrity of the maerl, even if the water had been left to flow into the Carnon River untreated. However, the pivotal issue turned out to depend not on the quality or quantity of scientific evidence, but rather on public perceptions derived from visible signs of pollution. One clear lesson which can be drawn from this is that investment in investigating and contributing to the formation of public perceptions is just as important as the more traditional investigations in scientific work per se. This is a lesson which is not only apposite for numerous ongoing debates about the best means of preventing or remediating mine water pollution elsewhere in the UK and Europe; it is potentially of wide applicability to risk-based environmental decision-making on the full range of waste, land and water management issues which confront decision-makers as they seek to achieve sustainable resource management.

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